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ION ACOUSTIC PARAMETRIC DECAY INSTABILITIES WITH STRONG ION LANDAU DAMPING

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Collective plasma phenomena similar to those occuring in the ionosphere upon incidence of intense electromagnetic waves have been studied in laboratory Q-machine plasmas ($T_e \simeq T_i$, no drifts). In particular, the ion acoustic parametric decay instability of particular interest with regard to the ionosphere, has been studied since it causes strongly enhanced absorption of electromagnetic waves.[1] Measurements on the ion acoustic instability

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($E \parallel B, \omega_{pe}/\omega_{ce} \lesssim 1$, $k_{\parallel}/k_{\perp} \gtrsim 1$) excited by an m=0 Gould-Trivelpiece plasma wave are reported. Two basic excitation regimes are investigated, one where the pump wavelength is very long, $m_{instHF} \gg 0$ (electromagnetic excitation) and one where the pump wavelength is finite, $m_{instHF} \gtrsim 0$, (electrostatic excitation).

For electromagnetic excitation, density dependence of instability threshold and instability threshold frequency shift were measured and found to be in agreement with expectations. However, measured saturated instability intensities show a much stronger pump intensity dependence than predicted by nonlinear saturation theories, and are in qualitative agreement with predicted dependences based on equilibrium changes.

For electrostatic excitation, measurements of frequency and wavelength for all three waves are in close agreement with the expected conservation relations. The low frequency oscillations are ion acoustic waves and the measured dispersion relation agrees with expectations.

ION ACOUSTIC PARAMETRIC DECAY INSTABILITIES WITH STRONG ION LANDAU DAMPING

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H. W. Hendel

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PUBLICATION REVIEW

This technical report has been reviewed and is approved.

Frederick C. Wilson
RADC Project Engineer

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ION ACOUSTIC PARAMETRIC DECAY INSTABILITY WITH STRONG ION LANDAU DAMPING

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ABSTRACT

Collective plasma phenomena similar to those occuring in the ionosphere upon incidence of intense electromagnetic waves have been studied in laboratory Q-machine plasmas ($T_e \approx T_i$, no drifts). In particular, the ion acoustic parametric decay instability, of special interest with regard to the ionosphere, has been studied since it causes strongly enhanced absorption of electromagnetic waves.[1] Measurements on the ion acoustic instability ($E \parallel B$, $\omega_{pe}/\omega_{ce} < 1$, $k_\parallel/k_\perp > 1$) excited by an m = 0 Gould-Trivelpiece plasma wave are reported. Two basic excitation regimes are investigated, one where the pump wavelength is very long, $m_{instHF} >> 0$ (electromagnetic excitation) and one where the pump wavelength is finite, $m_{instHF} \approx 0$ (electrostatic excitation).

For electromagnetic excitation, density dependence of instability threshold and instability threshold frequency shift were measured and found to be in agreement with expectations.

However, measured saturated instability intensities well above threshold are not consistent with present nonlinear saturation theories. In addition, equilibrium changes play an important role in determining steady-state instability amplitudes.

For electrostatic excitation, measurements of frequency and wavelength for all three waves are in close agreement with the expected conservation relations. The low frequency oscillations are ion acoustic waves and the measured dispersion relation agrees with expectations.

I. SUMMARY

The goal of the experimental program at Princeton University is to study phenomena in laboratory plasma associated with large amplitude RF electric fields for conditions similar to the ionosphere. The experiments are performed in Q-machine plasmas, which like the ionosphere, have comparable electron and ion temperatures.

Theoretical and experimental work had indicated that the anomalously high absorption of intense E.M. waves is due to excitation of parametric instabilities, i.e., one high-frequency wave close to the pump frequency and a low frequency wave, ion sound. In previous work we had shown that the wave-particle interactions lead to anomalous resistivity and an anomalous

collision frequency proportional to $(E_o/E_{crit})^2$,[1] and that the parametric instability is a very efficient heating mechanism.[2] (For a review of earlier work see Ref. 3.) Generally, our work is limited to the regime $\vec{E} \parallel \vec{B}$, $\omega_{pe}/\omega_{ce}<1$, $(k_{\parallel}/k_{\perp}>1)$.

Significant results obtained during the report period are divided into three areas: (1) detailed identification of the ion acoustic parametric decay instability, (2) observation of a zero frequency instability, and (3) identification of two instability saturation regimes, with equilibrium changes playing an important role in determining steady-state amplitudes.

The ion acoustic instability has been identified beyond doubt by checking frequency and wavelength matching conditions, density dependence of threshold pump intensity and frequency shift, and instability bandwidth dependences. All are in agreement with linear parametric instability theory. Two papers on intense stochastic ion heating by parametric instabilities have been published during the report period.[2]

A zero frequency instability is observed with threshold below the ion acoustic instability threshold. Strong plasma modification, however, does not occur, in contrast with the ion acoustic instability case. Frequency, axial damping, and wavelength measurements are consistent with identification of this instability as the purely growing (OTS) mode.

Near threshold, the observed strong dependence of the steady-state ion acoustic decay instability intensity upon pump intensity is in qualitative agreement with excitation of marginally stable waves by thermal fluctuations. However, a second

saturation regime when instability and pump intensities are comparable gives $\langle E^2_{inst}\rangle \propto E^2_{pump}$, and appears not to be in agreement with present saturation theories. Observed equilibrium changes due to the instability (heating, density reduction) play an important role in modification of both saturation regimes. First, near threshold, the strong dependence of instability intensity upon pump intensity implies that small changes in the threshold field (determined by the equilibrium) causes large changes in instability amplitude, leading in the extreme case to hard onset. Second, when $\langle E^2_{inst}\rangle \approx E_{pump}$, strong equilibrium changes occur, showing their importance in determining saturated instability intensity.

II. INTRODUCTION

The purpose of the experimental effort at Princeton University under the ARPA sponsored contract No. F30602-73-C-0163 is to study in controlled laboratory experiments the collective effects and their results relating to the present ionospheric modification program. Although much experimental and theoretical work has been reported,[3] a detailed identification of the instability for conditions similar to the ionosphere had not been performed in previous experiments. In addition, very little experimental information on the saturation mechanism limiting instability amplitudes exists.

The parametric instability is generated by the high frequency electric field of an $m = 0$ electrostatic or infinite wavelength electromagnetic wave, near the electron plasma frequency,

which decays into an electrostatic plasma wave and an ion acoustic wave. The unstable ion acoustic wave has a frequency much lower than the electron plasma frequency, and the unstable high frequency wave is downshifted from the pump frequency by the acoustic frequency. In the ionosphere the ion acoustic wave, and hence the parametric instability, is heavily damped due to comparable electron and ion temperatures, causing strong ion Landau damping. We also note that direct conversion to a pump electrostatic wave from the electromagnetic wave may take place in the ionosphere,[4] so that instability excitation by either pump wave must be considered.

It is therefore imperative to use a similarly damped plasma for the laboratory simulation experiments, i.e., a Q-device plasma, where the equilibrium temperature of the ions is somewhat higher than that of the electrons, and where the pump can either be a weakly damped electron plasma wave, or an infinite wavelength electromagnetic wave.

III. EXPERIMENT

The experimental work was performed on the Princeton Q-1, alkali metal, surface ionization plasma device. The magnetically confined plasma ($3 \leq \omega_{ce}/\omega_{pe} \leq 30$), Fig. 1, consists of ions produced by surface ionization of four Cs or K atomic beams incident on hot tungsten ionizer plates at both ends of the plasma column and of thermionic electrons emitted from these plates. T_i is typically $1\text{-}3T_e$, where $T_e = 0.2$ eV, $10^{-1} < \nu_{ei}/\omega_{pi} < 5$, and $10^8 < n < 2 \times 10^{11}$ cm^{-3}. The three-cm-

diameter end plates are aligned perpendicular to the magnetic field. The plasma column is approximately one meter long. The plasma is fully ionized. No voltage is applied to the plasma column, and no equilibrium axial currents are present. The ion density can be kept constant with an axial deviation of less than 1%.

The plasma diagnostics consist of Langmuir probes, ion temperature probes, high frequency probes, and microwave cavity. Langmuir probes and cavity measure both density and electron temperature. Special probes with high-frequency response measure the instability frequency spectrum. Probes can be used in 20 positions throughout the plasma and all probes can be moved radially in and out of the plasma column. Axially movable probes allow motion along a B-field line over 20 cm. The magnetic field can be varied from zero to seven KG, however, large plasma losses set in below approximately 2 KG, i.e., $\omega_{ce} > \omega_{pe}$ for the experiments described.

The excitation of the parametric instability was done in a number of ways, by resonant cavity, grids or grid, single wire probes, and by rings surrounding the plasma column. Sensitive high and low-frequency interferometers were set up to measure instability wavelengths.

IV. RESULTS

The significant results of this work are: A. Detailed identification of the ion acoustic parametric decay instability; B. Observation of a zero-frequency instability below the ion

acoustic threshold, tentatively identified as the purely growing mode; C. Observation of two saturation regimes, one near threshold, and one at high pump intensity, where instability intensity is comparable to pump intensity. The significance of equilibrium changes in both regimes is discussed.

A. Ion Acoustic Instability

a) Measurements of Frequency and Wavelength Sum Rules

Frequency sum rules (Fig. 2) were found to be satisfied with $\leq$ 5% precision over a wide range of parameters. For densities below $10^{10}\mathrm{cm}^{-3}$, low-frequency wavelengths can be measured (showing coherence over many wavelengths) and axial wavelength sum rules were satisfied (Fig. 3) to $\approx$ 10% for all waves involved ($\vec{k}_{pump} = \vec{k}_{instHF} + \vec{k}_{instLF}$). The occurrence of coherent low-frequency wavelengths is somewhat surprising, since ion acoustic ($T_e \approx T_i$) waves should damp in approximately one wavelength. However, for these measurements, the high-frequency wavelengths were fixed by boundary conditions ($m_{pump} = 0$, $m_{inst.HF} \leq 4$); to ensure momentum conservation the acoustic wavelength must be coherent. Thus, the coherence of the acoustic wavelength is determined by the coherence of the high-frequency waves. Figure 4 shows the measured acoustic dispersion relation for these conditions.

b) Instability Regimes

Dependence of acoustic frequency (or equivalently, frequency downshift Δf from pump) upon ω/ω_p is shown in Fig. 5. Two regimes exist, $m_{pump} \approx m_{instabHF}$, and $m_{pump} << m_{instabHF}$. When the pump wavelength cannot be neglected (i.e., electrostatic

excitation), it determines the frequency shift Δf through the momentum conservation equation (Figs. 5, 6). In the regime where $m_{pump} << m_{instHF}$ and the pump wavelength can be neglected (electromagnetic excitation), frequency measurements (Fig. 7) show $\Delta f = f_{IA} \simeq f_{pi}/5$ or $k_{inst}\,\lambda_d \simeq .2$ for the most unstable mode ($\nu_e < \Delta f$, $Q \simeq 1$, $10^8 < n < 10^{11}cm^{-3}$), consistent with Ref. 5. In addition, threshold dependence upon density over the same range of parameters shows $E^2_{th}\ \alpha\ n^{3/2 \pm 1/4}$ (Fig. 8) in agreement with collisional fluid theory: $E^2_{th}/4\pi nT\ \alpha\ (\nu_e/\omega_p)$. The density dependence of ion damping is negligible $\nu_i \simeq \omega_{IA} \simeq \nu_{iLD} >> \nu_{icoll}$, and thus can be neglected in the threshold equation. Another less well understood instability exists with $\Delta f \simeq f_{pi}$. Measurements also show the instability intensity ratio $E^2_{instLF}/E^2_{instHF} \simeq 10^{-4}$, constant over many decades (Fig. 9), consistent with the Manley-Rowe relations. Nonlinear saturation theories predict other dependences.

c) Measurements of Instability Bandwidth

Instability "Q" measurements ($Q \equiv \Delta f$/bandwidth) show that the smallest damping frequency, ν_e for plasma waves, ν_i for ion acoustic waves, determines the instability bandwidth. For example, in our plasma $\nu_i \simeq f_{IA} = \Delta f$, and when $\nu_i > \nu_e$, the instability bandwidth is narrow $\simeq \nu_e$ ($Q > 1$), rather than $Q \simeq 1$ as expected for the ion acoustic wave alone. When plasma wave damping dominates, $Q \simeq 1$ (see Fig. 10). This can be understood by considering high and low-frequency waves as harmonic oscillators. The associated damping frequency permits direct excitation of the oscillator by a pump, even if the pump has a frequency

off-resonance, as long as the difference is less than the collision frequency, i.e., the damping frequency indicates how easily an oscillation can be excited off-resonance. For the parametric instability, however, momentum and frequency conservation rules must also be satisfied. Since from boundary conditions the HF wave has a well-defined wavelength, maximum deviation from the center frequency (determined by the plasma wave dispersion relation) is ν_e. Since $k_{IA} = k_{pump} - k_{instHF}$ is also fixed (momentum conservation), the maximum deviation from $\omega_{IA} = C_{IA}k_{IA}$ is ν_i. However, since the instability spectra at both high and low frequencies must be the same (frequency conservation), the maximum bandwidth is thus the bandwidth of the least damped wave.

d) Intense Stochastic Ion Heating by the Low-Frequency Part of the Parametric Ion Acoustic Instability

See enclosed publication.

B. Zero Frequency Instability

An instability having approximately zero-frequency shift and steady-state intensity $E^2_{inst} \propto (E^2_{pump})^2$ is observed with threshold well below the parametric ion acoustic decay instability threshold (see Fig. 11). However, plasma heating and modification are not observed until after onset of an ion acoustic instability. Associated with the widening of the signal at the pump frequency a peak at zero frequency (50 KHz bandwidth) is observed. In addition, zero-frequency axial modulation with characteristic length equal to $\lambda_{\parallel pump}/2$ is observed, consistent with expectations for the purely growing mode with finite wavelength pump. Axial

measurements (Fig. 12) show strong damping of the pump (1 KHz bandwidth), leaving only a broad band ($\approx$ 50 KHz) spectrum at the pump frequency, with integrated energy density comparable to that of the original pump wave.

Parametric coupling to drift waves, Kelvin-Helmholtz waves, or ion cyclotron waves is ruled out by their absence in the instability spectra. Also, a nonzero frequency, long wavelength ion acoustic parametric instability is unlikely, because this mode cannot exist at low densities where $\lambda_{mfp} >> L_{machine}$. At very high densities where such an instability might exist, no specific low-frequency peaks were observed, only a broad spectrum with width $\approx$ 100 KHz. All of the above results are consistent with the following physical model of the PGM: An m = 0 pump electron plasma wave is launched, due to nonlinear action with low-frequency fluctuations (at threshold) m = 0 plasma waves at the pump frequency are excited, and the resulting standing wave enhances low-frequency (density) modulations by changing plasma equilibrium with characteristic length $\lambda_{pump}/2$ leading to growth of the unstable high-frequency wave by enhanced scattering of the pump wave. A similar coupling mechanism between high and low frequency generates the better-understood ion acoustic parametric instability.

C. Instability Saturation

Two experimental ion acoustic instability saturation regimes exist. Near threshold, $\langle E^2_{inst}\rangle \propto (E^2_{pump})^{\ell}$; where $\ell \geq 4$ ($n \approx 10^{10}cm^{-3}$, $\lambda_{mfp} < L_{machine}$). Well above threshold , when $\langle E^2_{inst}\rangle \approx E^2_{pump}$, $\langle E^2_{inst}\rangle \propto E^2_{pump}$, i.e., $\ell \approx 1$. Also,

$\langle E^2_{instLF}\rangle/\langle E^2_{instHF}\rangle \approx \text{const} \approx 10^{-4}$, independent of E_{pump}. In addition, no evidence of instability cascading or spectral broadening is observed as E_{pump} is increased -- only one ion acoustic instability is present, see Fig. 11.

A simple theory is consistent with observations near threshold ($E_{pump} \approx E_{cpump}$). Just below threshold, the instability amplitude can be excited by thermal fluctuations, Cherenkov emission of acoustic and electron plasma waves by ions and electrons in thermal equilibrium (see for example, work by Landau,[6] or Tsytovich[7]):

$$\langle E^2_{inst}\rangle \approx \frac{A}{\gamma} \alpha \frac{A}{|E^2_{pump} - E^2_{cpump}|} \; ; \; \ell \approx \frac{E^2_{cpump}}{E^2_{cpump} - E^2_{pump}} >> 1,$$

where E^2_{cpump} is the threshold pump field and A is a source term due to thermal fluctuations. Note that small equilibrium changes by the instability (density reduction, electron heating) cause a corresponding drop in E^2_{cpump}, ($E^2_{cpump} \alpha\, n^{3/2}/T_e^{1/2}$). However, since $\ell >> 1$, small changes in E_{cpump} cause large changes in ℓ, showing the importance of equilibrium changes in determining instability amplitudes in this regime.

Many theories predict the dependence of $\langle E^2_{inst}\rangle$ upon E^2_{pump} in the high-pump intensity regime. The saturation theories of Valeo, Perkins and Oberman[8] and Dubois and Goldman[9] do not apply, since they predict $\ell = 2$ with instability cascading, and $\langle E^2_{instLF}\rangle/\langle E^2_{instHF}\rangle \alpha E^2_{pump}$. Saturation occurs when the instability intensity is itself large enough to excite a parametric

instability. A physical argument of DeGroot and Katz[10] predicts instability saturation (and subsequent spectral broadening) due to severe electron trapping by the unstable electron plasma wave. This condition is determined by the fact that only electrons in the velocity range $\omega/k \pm (2e\Phi/m)^{1/2}$ are trapped in the wave potential; when $(\omega/k)^2 \approx 2e\Phi/m$, $\omega/k > v_{the}$, all electrons are trapped. Substituting $E_{max} = k\Phi$ gives the result: $E_{max} \approx m/2e\ \omega^2/k$, and $\ell = 0$, the instability amplitude is independent of pump amplitude. This could apply to our experiment, since $e\Phi_{pump}/KT_e > 1$, however the results ($\ell \approx 1$, no spectral broadening) are not in agreement with this picture.

Another possible saturation mechanism, insufficient growth before the unstable waves convect out of the pumped region leads to:

$$\langle E^2_{inst} \rangle \approx \frac{A}{\gamma} (e^{\gamma t}-1)$$

where γ is the parametric instability growth rate, and A the Cherenkov wave emission term. For $\gamma t << 1$, $\langle E^2_{inst} \rangle \approx At$ and $\ell = 0$, if A is not modified by the presence of an RF pump. However, if this condition causes saturation above threshold, it must modify the physics near threshold: $\langle E^2_{inst} \rangle \approx A/|\gamma|(1-e^{|\gamma|t}) \approx At$. This result is in disagreement with observed behavior in the low pump intensity regime, ruling out saturation by insufficient growth. A similar argument applies if we assume $\langle E^2_{inst} \rangle \propto \gamma t$.

A fourth saturation theory, by Bezzerides and Weinstock,[11] modification of particle orbits by the instability, leads to

$$\langle E^2_{inst}\rangle \propto \left\{ \ell n \left[\frac{E^2_{pump}}{E^2_{cpump}} \right] \right\}^2 ,$$

or $\ell < 1$. This theory requires significant wave-particle interactions -- the conditions where electron trapping becomes important. Although present data suggests strongly that $\ell \approx 1$ regardless of pump intensity, we cannot yet rule out this possibility. A final saturation mechanism comes from the work of Tsytovich.[7] If the frequency matching conditions are not perfect, so that $\omega_{pump} - \omega_{HF} - \omega_{LF} >> \gamma$, where γ is the characteristic growth time of the instability, the normal coherent wave theory of the parametric instability is not applicable. Using the random phase approximation, Tsytovich derives an instability wave equation. The results are formally identical to the quantum-mechanical decay of a pump wave into high and low-frequency waves. Saturation is possible, since a new loss mechanism can occur when the instability amplitudes become significant -- inverse parametric decay. Solving the wave equation in the one-dimensional approximation, with the instability intensity ratio $\langle E^2_{LF}\rangle/\langle E^2_{HF}\rangle << 1$, we obtain:

$$\frac{\langle E^2_{LF}\rangle}{\langle E^2_{HF}\rangle} \simeq \frac{\omega_{IA}}{\nu_{IA}} \frac{\nu_e}{\omega_{pe}} \simeq \frac{\nu_e}{\omega_{pe}} = \text{const}; \ \langle E^2_{HF}\rangle \propto E^2_{pump} ,$$

in qualitative agreement with observations. The interesting point here is that no additional nonlinear effects (mode cascading, trapping) are necessary to obtain saturation; only finite instability amplitudes.

V. CONCLUSIONS

The ion acoustic parametric decay instability for the ionospheric regime $T_e \simeq T_i$ is identified beyond doubt by measurements of ω and k, threshold and frequency-shift density-dependence, spectral bandwidth, and intensity relations. High and low-frequency spectra are shown to be identical in shape and give the expected frequency matching condition. Wavelength measurements on all three waves also agree closely with the wavenumber matching condition. The dependence of threshold frequency shift upon density (electromagnetic excitation) agrees with linear theory. In addition, instability bandwidth measurements, and threshold dependence upon density are in agreement with linear collisional fluid theory, but with a phenomenological ion Landau damping term included.

An instability with threshold well below the ion acoustic instability and having approximately zero-frequency shift Δf from the pump is observed. Associated with this instability is strong axial damping of the pump, leaving only a broad spectrum without a pump signal. This is tentatively identified as the purely growing mode.

Finally, two steady-state ion acoustic instability regimes exist. At threshold, the instability intensity grows rapidly

with pump intensity, consistent with excitation by thermal fluctuations. Also, in this regime, small changes in equilibrium due to heating by the instability, density reduction and electron heating can cause large changes in instability amplitude. Well above threshold, when instability and pump intensity are comparable, a saturation regime exists where instability and pump intensities are approximately proportional.

Existing nonlinear theories are not in agreement with observations, for instance, under the conditions of equal ion and electron temperatures <u>no</u> instability cascading is observed, in disagreement with the generally accepted saturation mechanism of nonlinear ion Landau damping. The saturation mechanism is tentatively identified as due to inverse parametric decay.

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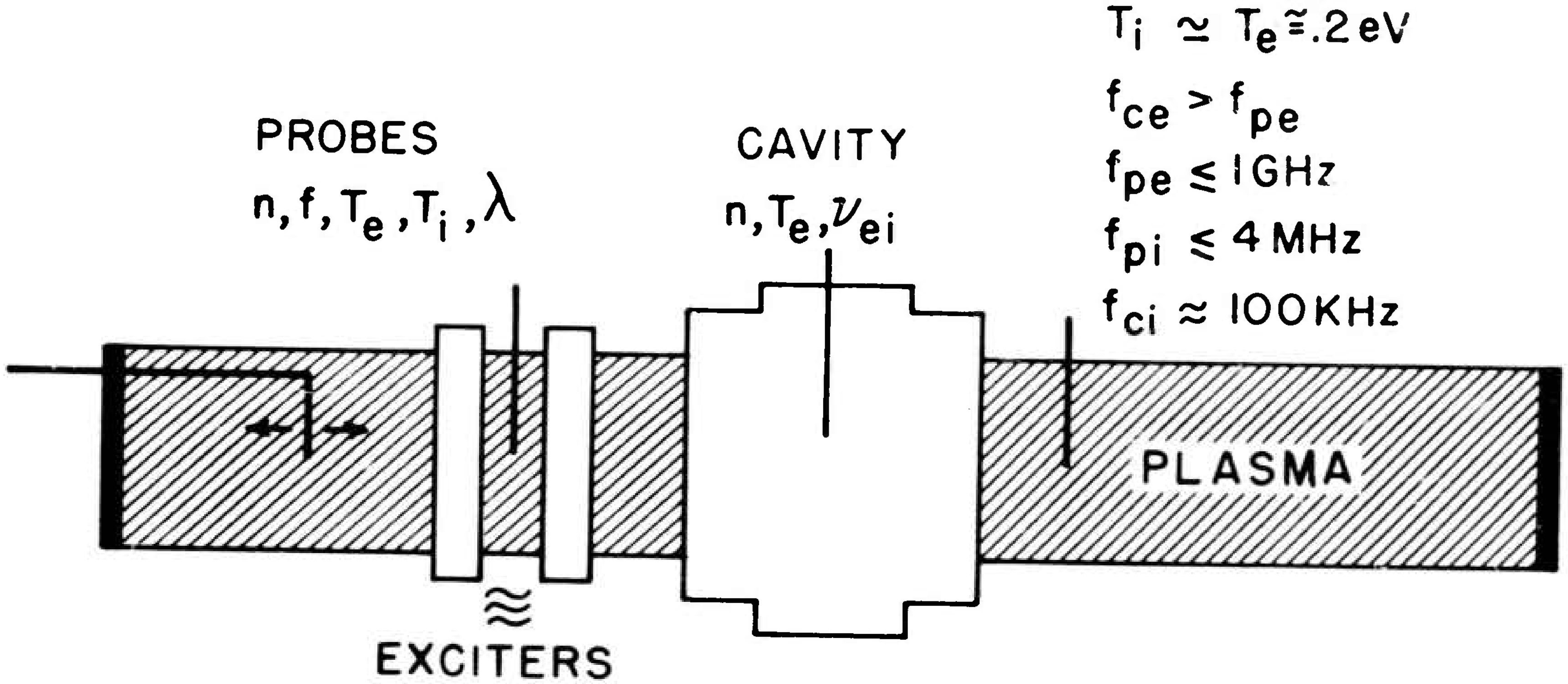

Fig. 1. Machine configuration. Typical experimental conditions are indicated. Parametric instability is excited by ring probes surrounding the plasma, or by cavity.

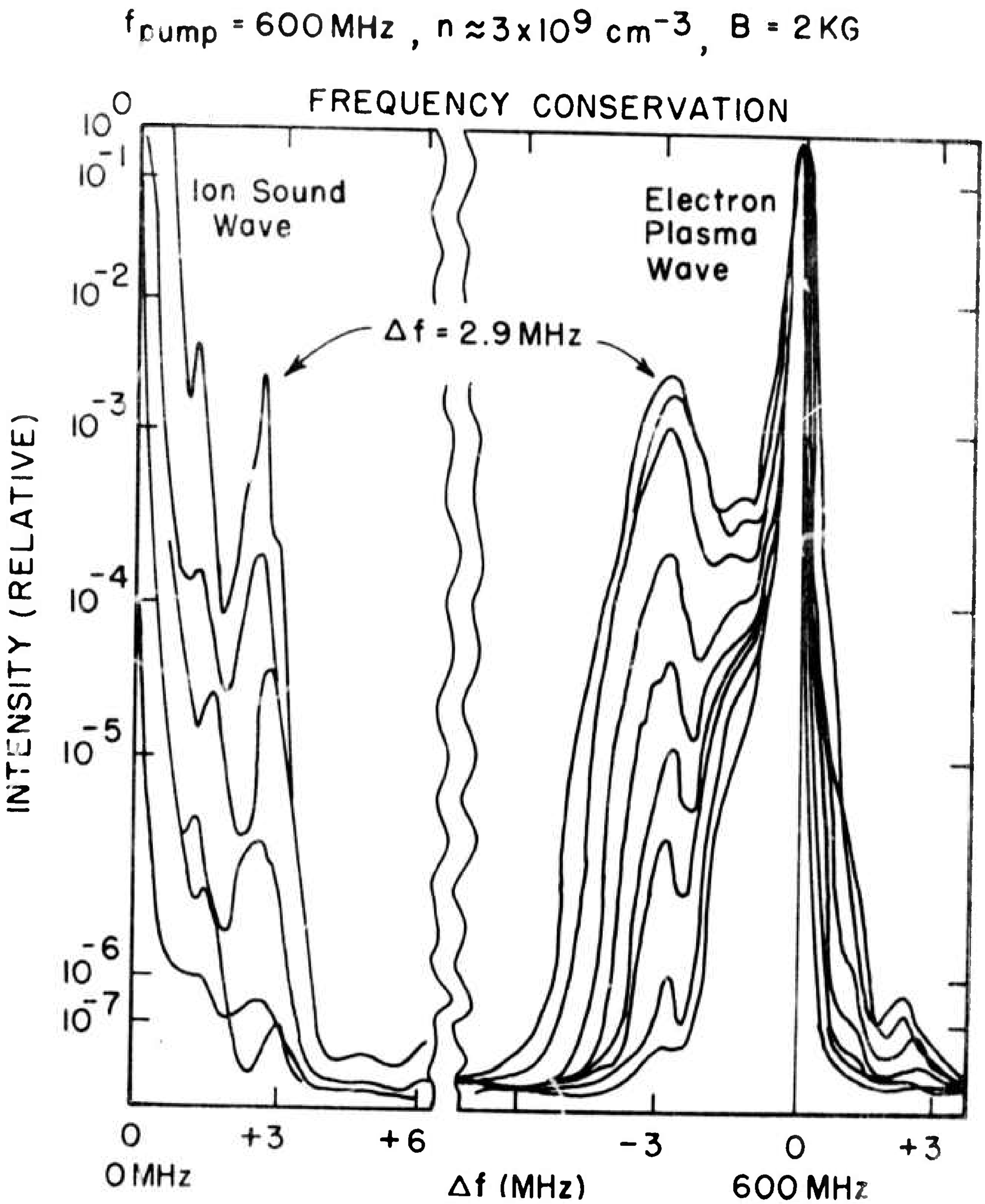

Fig. 2. Typical instability frequency spectrum, showing frequency conservation relation is well-satisfied.

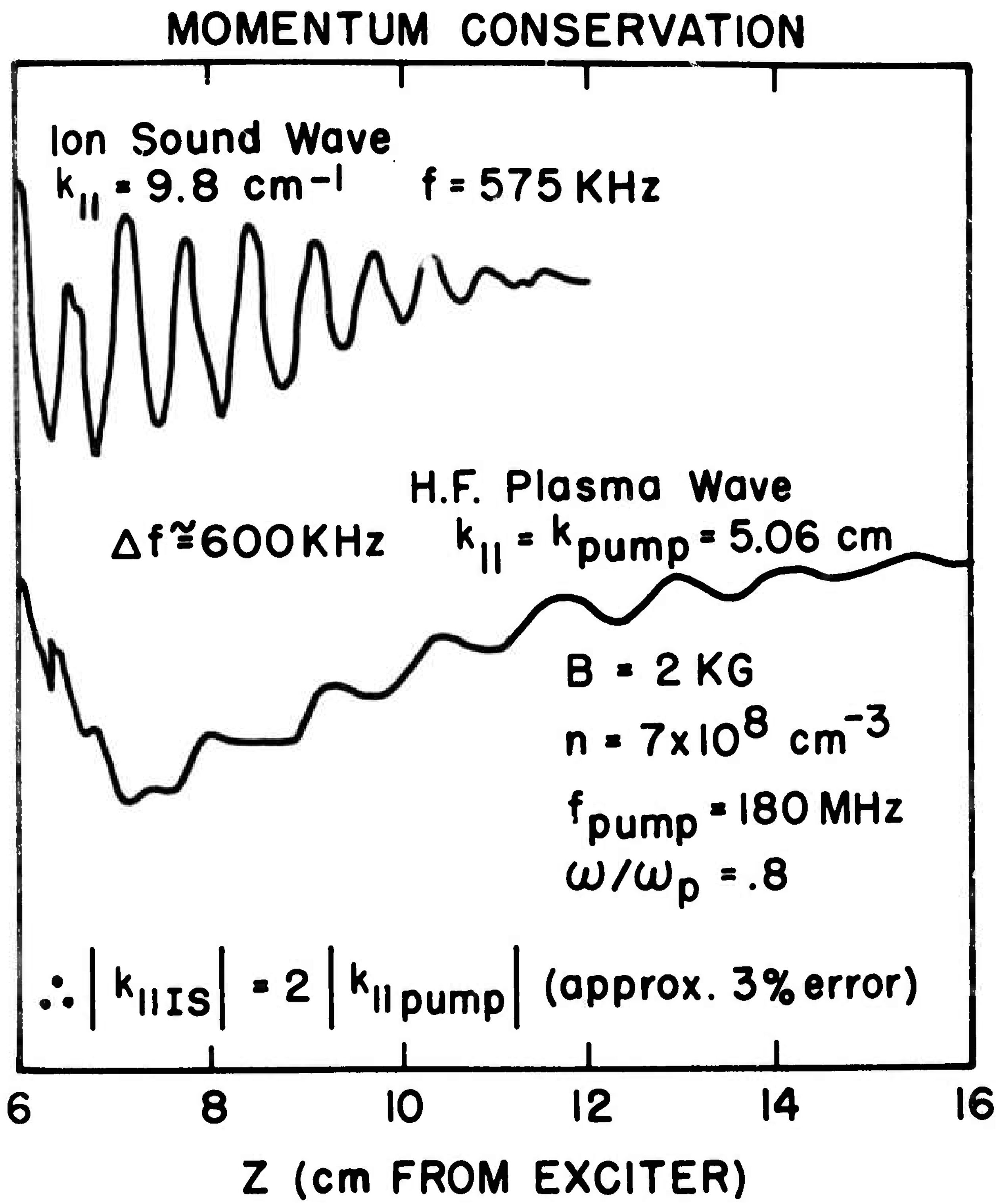

Fig. 3. Typical wavelength measurements, showing momentum conservation.

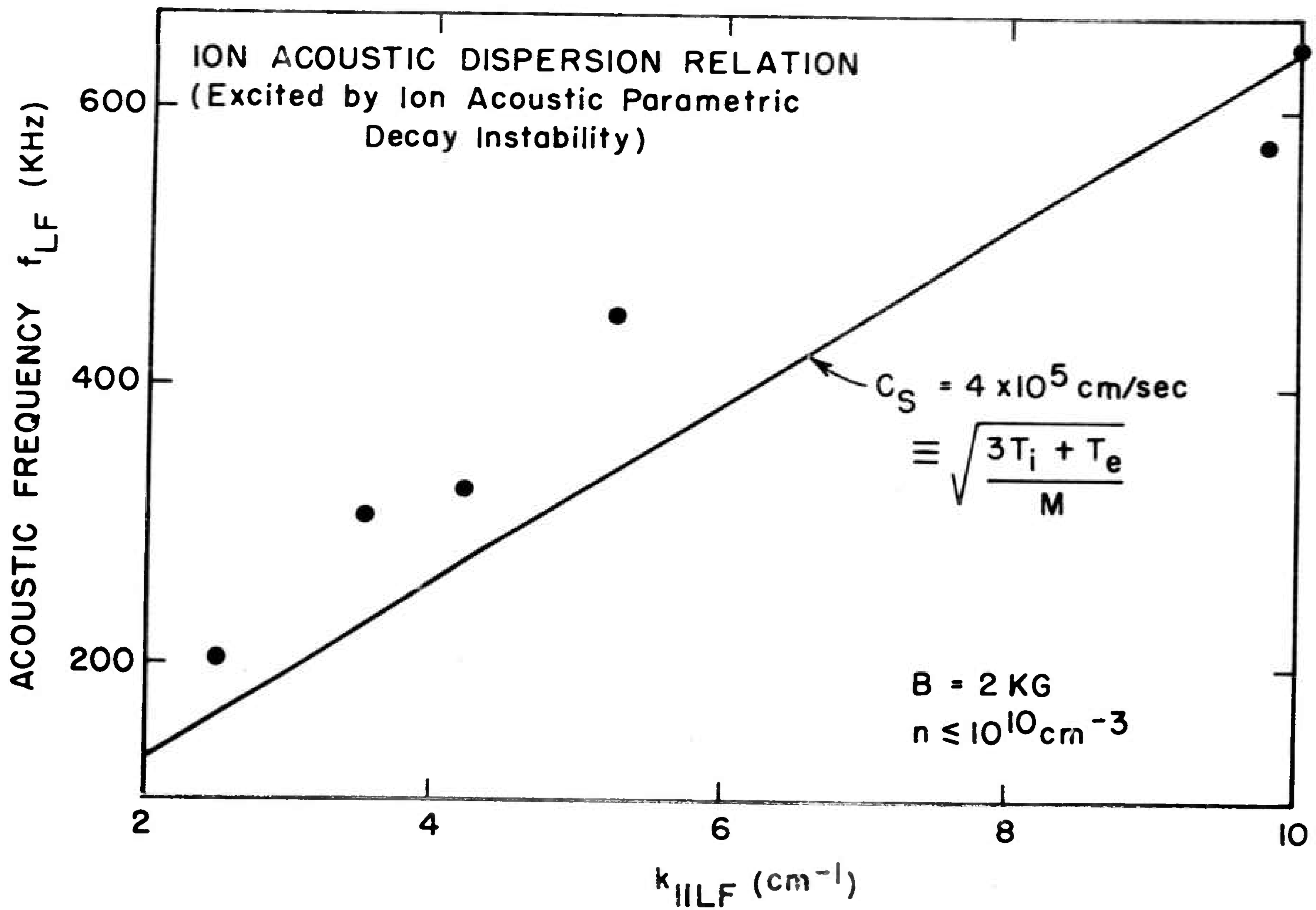

Fig. 4. Ion Acoustic dispersion relation determined from parametric instability wavelength measurements of the low frequency spectrum.

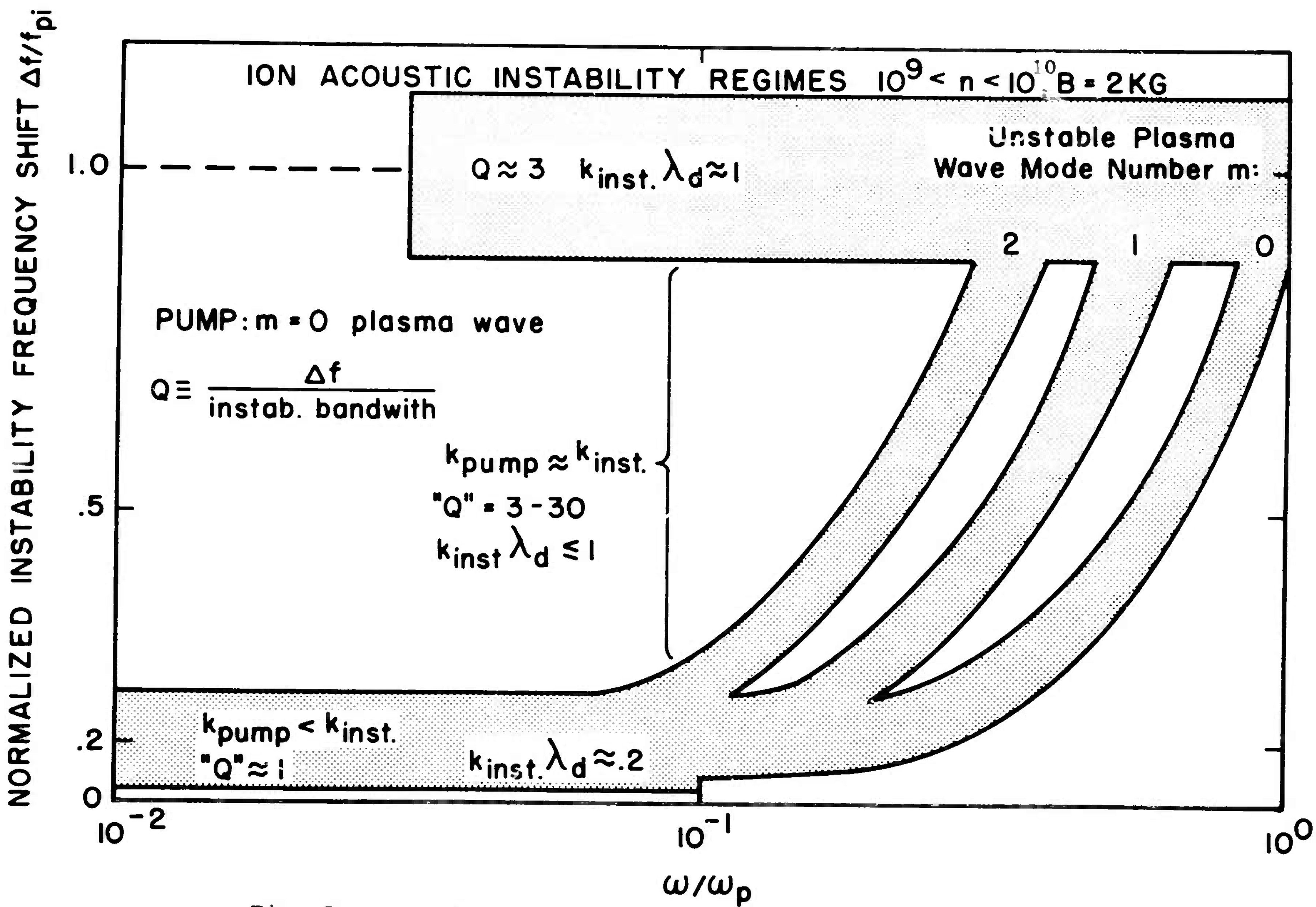

Fig. 5. Overall view of ion acoustic parametric instability, showing acoustic frequency, (or equivalent frequency Δf) against ω/ω_{pe}.

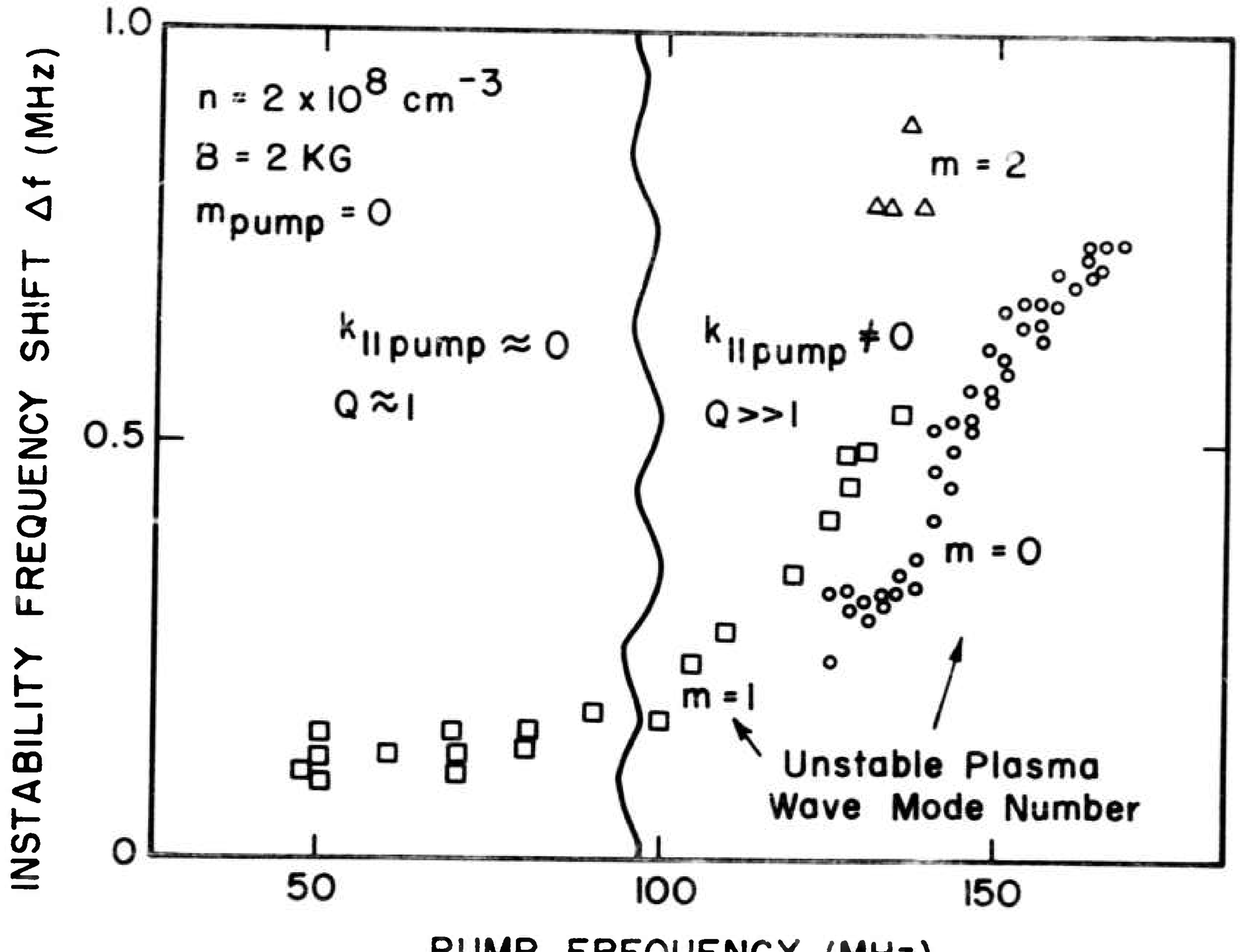

Fig. 6. Typical instability frequency dependence upon pump frequency when $k_{instHF} \approx k_{pump}$ $(m_{instHF} \simeq m_{pump})$ at threshold.

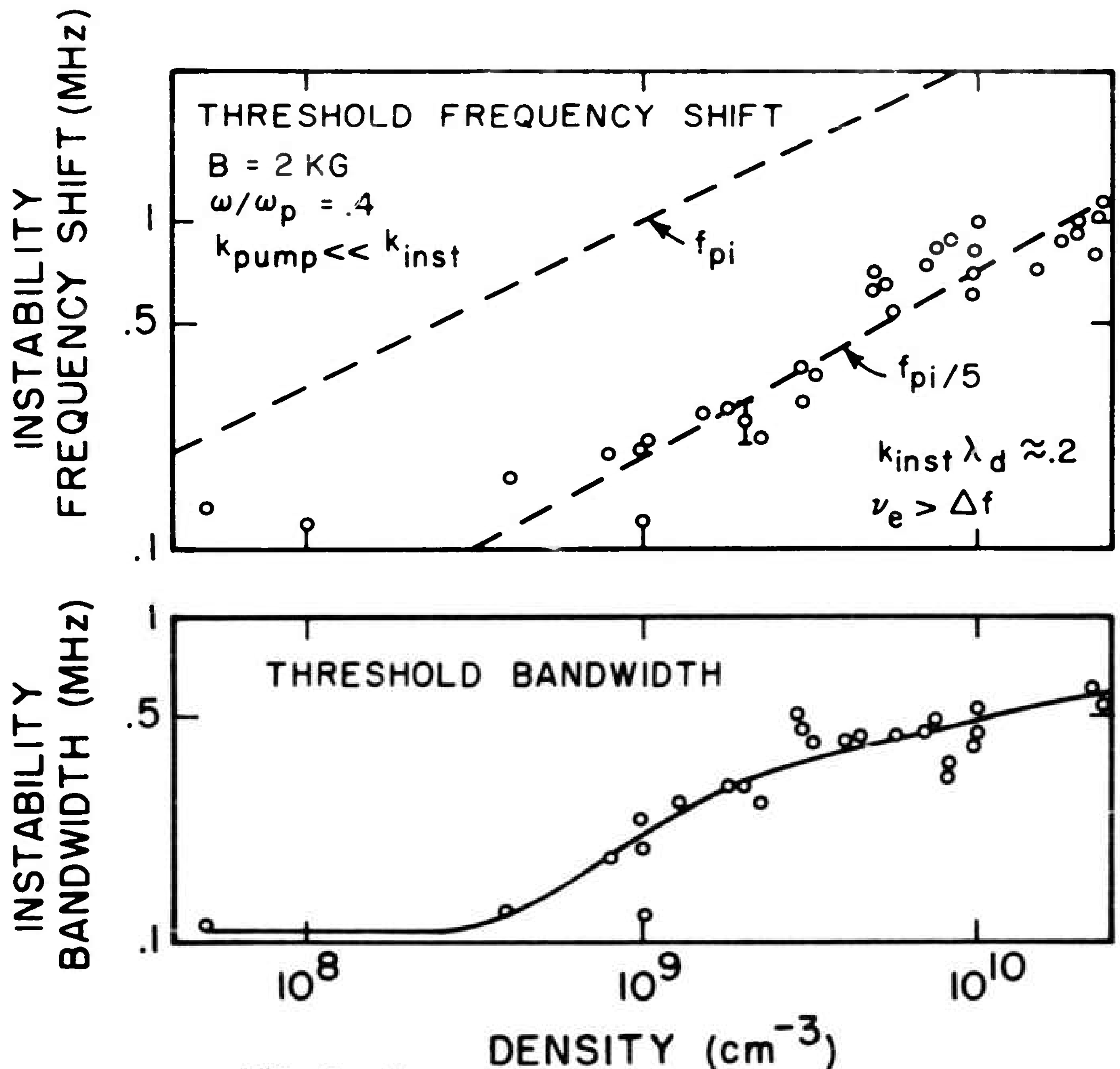

Fig. 7. Frequency shift for E. M. wave excitation and bandwidth.

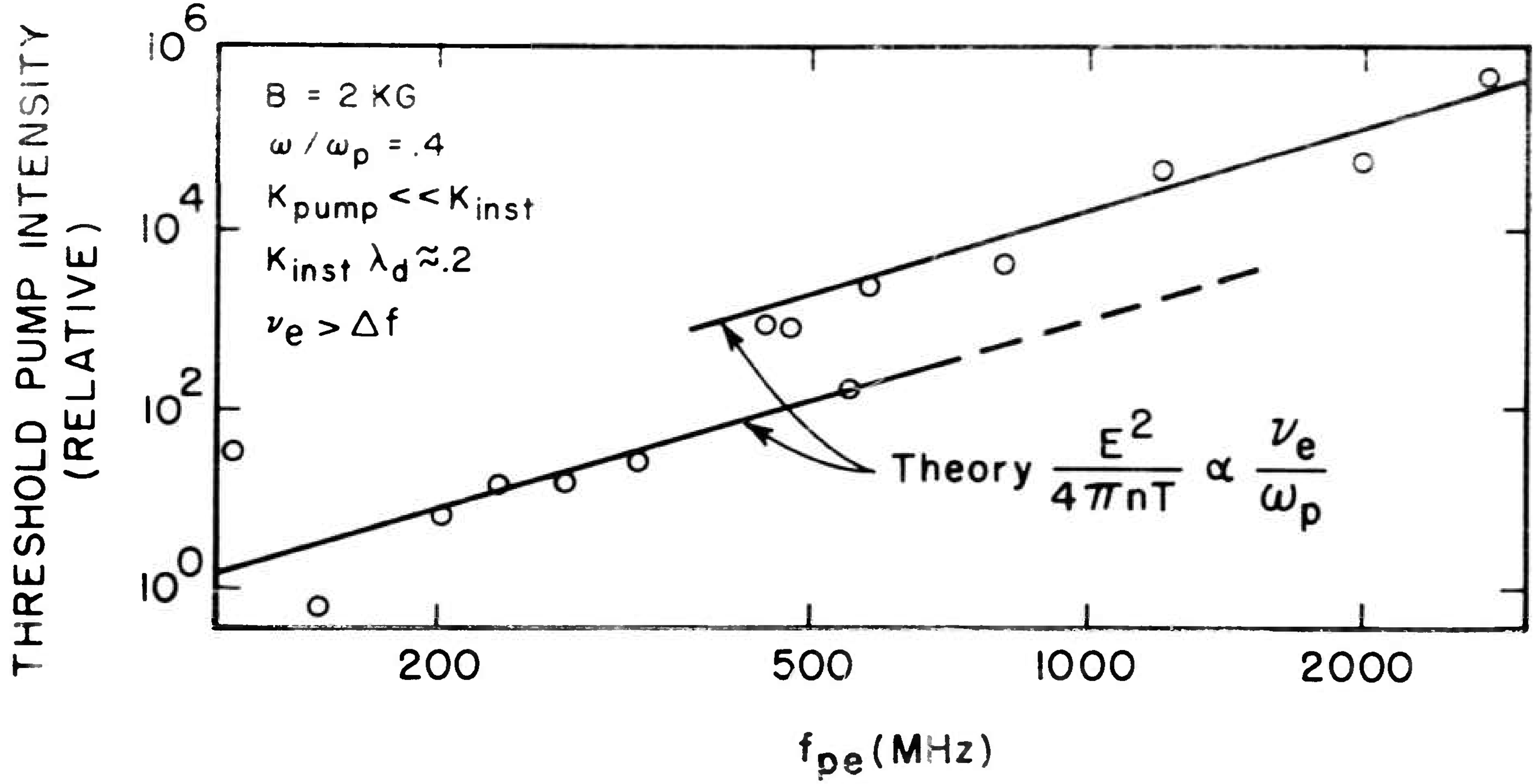

Fig. 8. Threshold pump intensity dependence upon density for E.M. wave excitation.

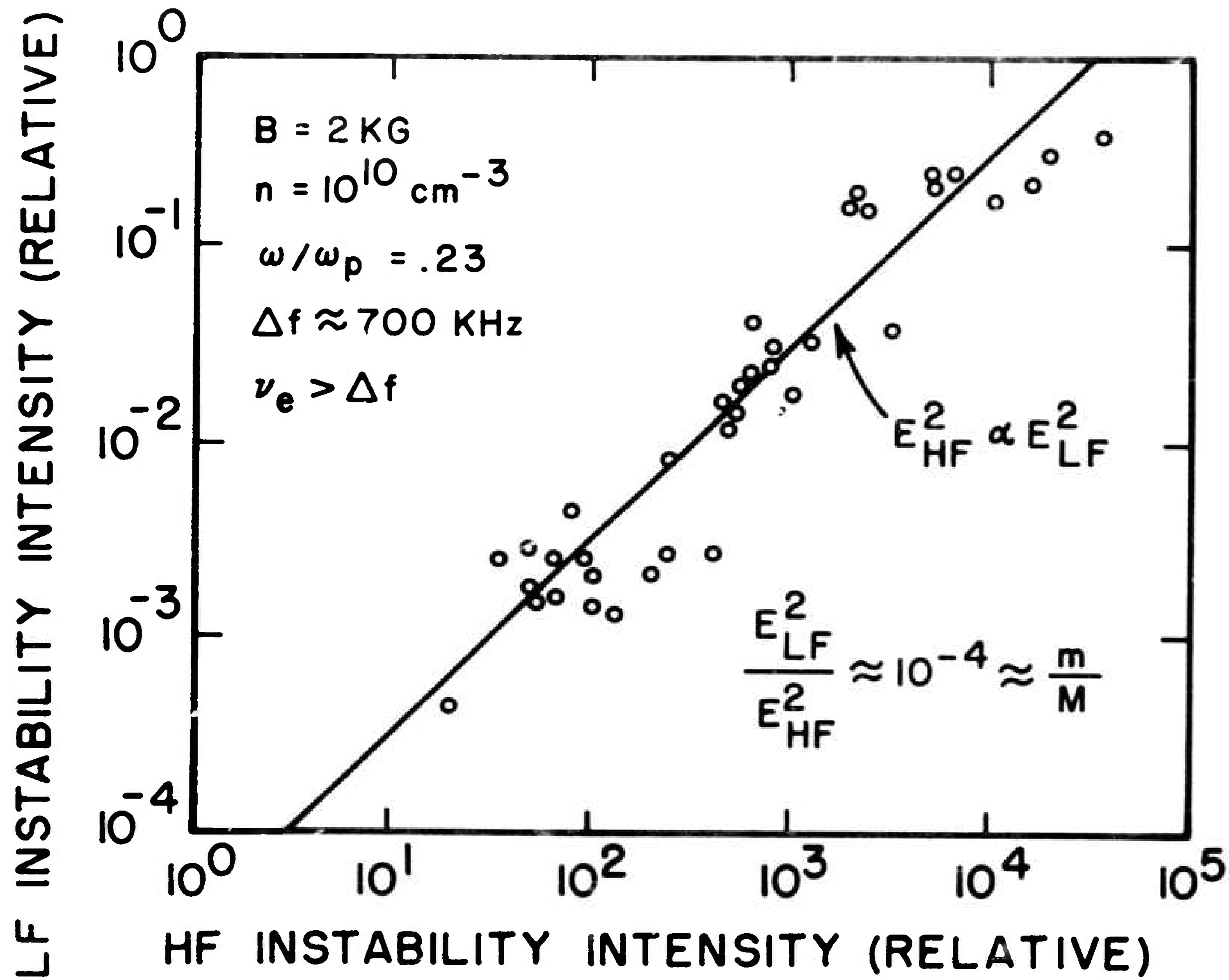

Fig. 9. High frequency to low frequency intensity ratio.

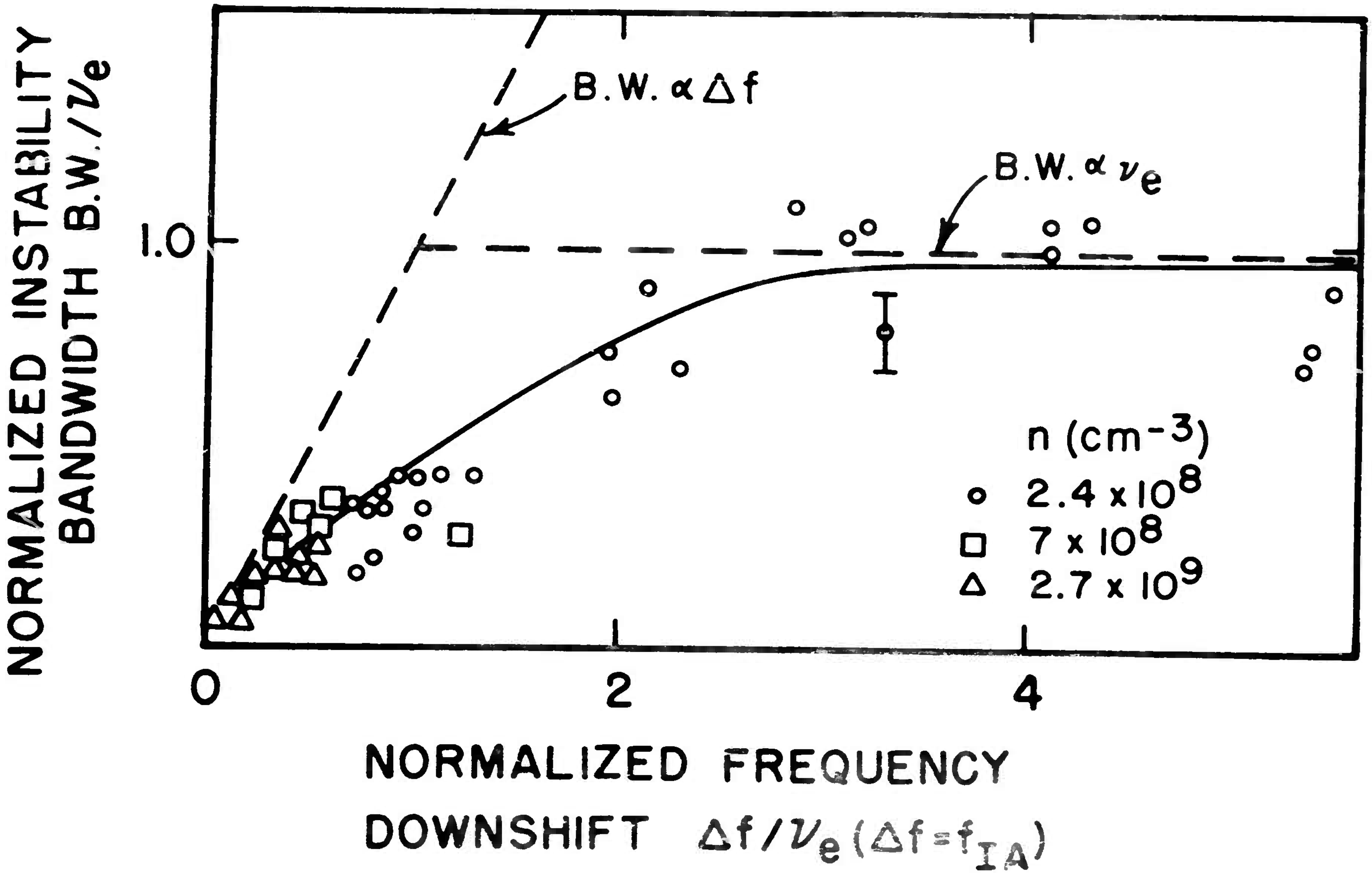

Fig. 10. Instability bandwidth dependence upon frequency shift.

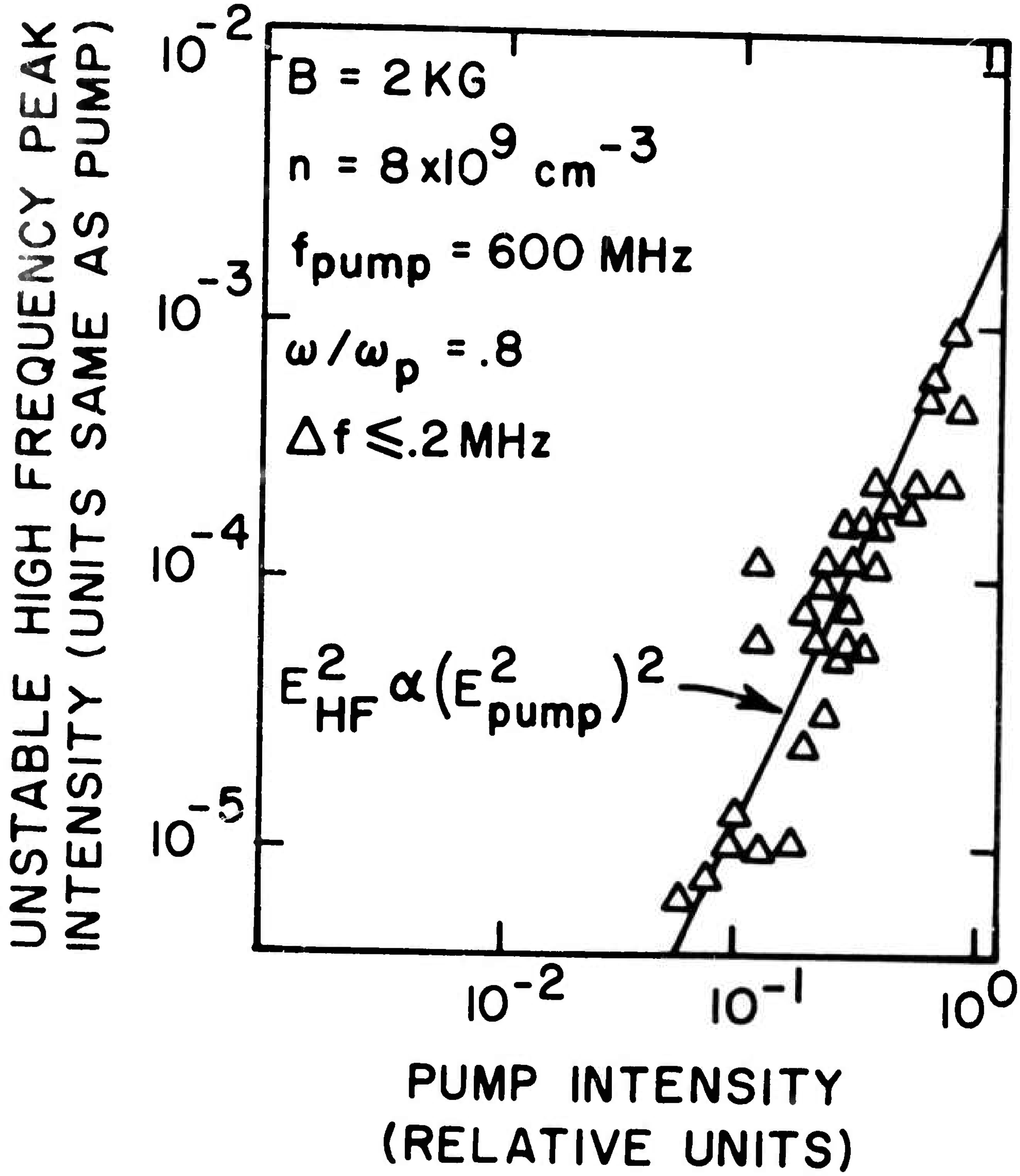

Fig. 11. High frequency portion of the "zero" frequency instability, intensity dependence upon pump intensity.

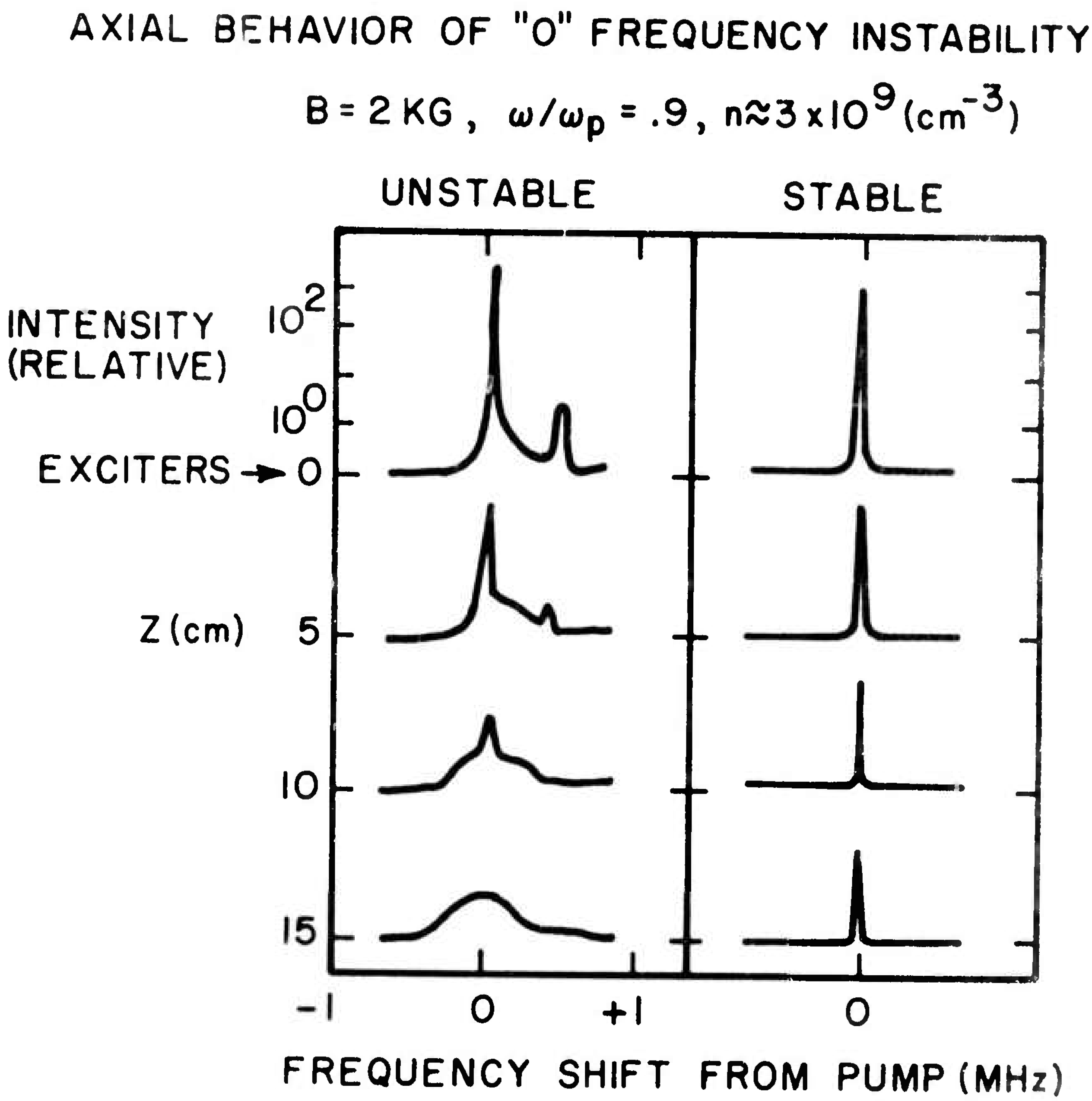

Fig. 12. Axial behavior of "zero" frequency instability.

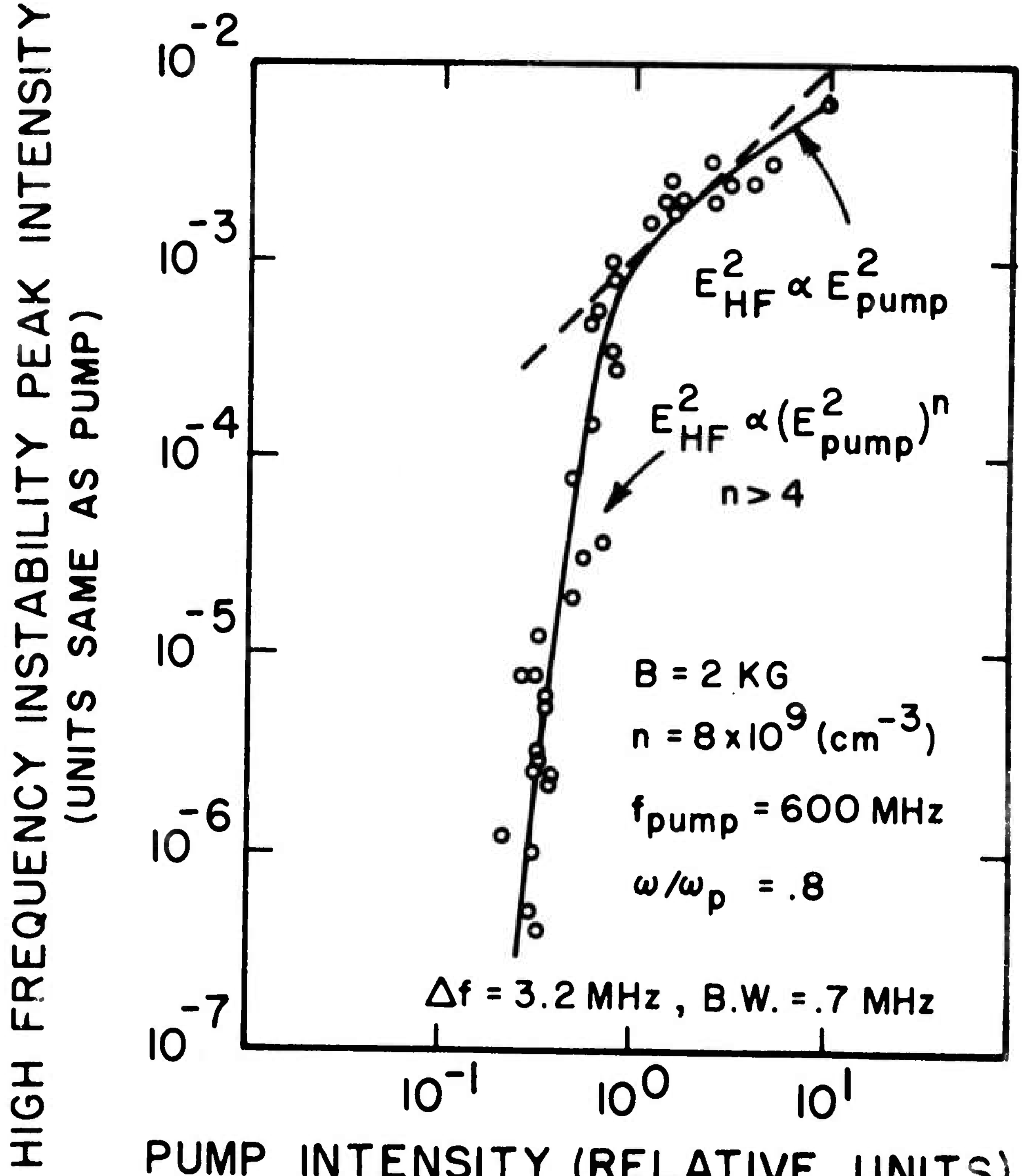

Fig. 13. High frequency ion acoustic instability dependence upon pump intensity.